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# Polarized lepton nucleon scattering — summary of the theory talks on spin physics at DIS 99

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We summarize the theory talks given in Working Group 4 'Polarized Lepton Nucleon Scattering' at the DIS 99 workshop. The significant progress made over the last year on many of the interesting topics in 'spin physics' is documented.

## 1. INTRODUCTION

Spin physics has been going through a period of great popularity and rapid developments ever since the measurement of the proton's spin structure function $g_1$ by the EMC [ 1] more than a decade ago. As a result of combined experimental and theoretical efforts, we have gained some fairly precise information concerning, for example, the quark spin contribution to the nucleon's spin. Yet, many other interesting and important questions, most of which came up in the wake of the EMC measurement, remain unanswered so far, the most prominent 'unknown' being the fraction of the nucleon's spin carried by gluons. Future dedicated spin experiments (for a compilation, see [ 2]) are expected to further improve our knowledge about this, and other, topics.

We will organize this paper by first taking stock and summarizing some main aspects of what has been learned about the nucleon's spin structure from experimental data on deep inelastic scattering (DIS) of polarized leptons and nucleons. Here we will mainly refer to talks [ 3, 4, 5] given at this conference, in which next-to-leading order (NLO) QCD fits to the available DIS data were presented.

The second part of this paper will address the yet open questions in spin physics, most of which were discussed at this workshop. Some of the main issues here are the need for further information on the nucleon's spin-dependent parton densities, in particular on its gluon, the so far unmeasured transversity densities, the orbital angular momentum carried by partons in the nucleon, spin-transfer in fragmentation processes, and single-spin asymmetries. Note that there is substantial overlap among some of these topics, so that a distinction between them in this work may at times look somewhat artificial. On all these topics, and on others as well, significant and very recent theoretical advances were reported at this conference. In many cases, the progress made is of direct importance for future experimental studies.

## 2. INFORMATION FROM POLARIZED DEEP INELASTIC SCATTERING

Our present knowledge about the spin structure of the nucleon derives almost entirely from inclusive DIS of longitudinally polarized leptons and nucleons. Here, experiments measure, for various targets, the spin asymmetry

$$A_1(x,Q^2) \approx \frac{g_1(x,Q^2)}{F_2(x,Q^2)/[2x(1+R(x,Q^2))]} \; , \tag{1}$$

where $F_2$ is the unpolarized structure function and $R = F_L/2xF_1$. $g_1$ is directly related to the spin-dependent (anti)quark and gluon densities $\Delta q = q^+ - q^-$, $\Delta g = g^+ - g^-$. To NLO of QCD, which currently is the 'state-of-the-art' in the theoretical description, one has

$$g_1 = \frac{1}{2}\sum_q e_q^2 \Big[ (\Delta q + \Delta\bar{q}) \otimes \Big(1 + \frac{\alpha_s}{2\pi}\Delta C_q\Big) + \frac{\alpha_s}{2\pi}\Delta g \otimes \Delta C_g \Big] \; , \tag{2}$$

where $\Delta C_q$, $\Delta C_g$ are the NLO terms in the coefficient functions. The polarized parton densities evolve in $Q^2$ according to the spin-dependent NLO DGLAP [ 6] equations. Note that beyond lowest order (LO), the parton densities are not unique but refer to the factorization scheme adopted in removing the collinear singularities occurring in the calculation of the NLO QCD corrections. This scheme dependence of the parton densities is compensated by that of the coefficient functions in such a way that a physical quantity like $g_1$ remains, to the order considered, unaffected by any change in the factorization scheme. In other words, the physics content of phenomenological fits to data has to come out the same, irrespective of the scheme chosen, if the analysis is performed properly.

Several NLO fits to the polarized DIS data were published in the last few years [ 7, 8, 9]. At this workshop, two updates of previous fits were presented [ 3, 4], using the most recently available experimental information. It should be noted that inclusive DIS will in principle only determine the sum of the polarized quark and antiquark distributions for each flavour, but not allow an immediate decomposition into, say, sea and valence parts. Semi-inclusive measurements in DIS (see [ 2, 5]), which in principle could help out of this situation, are presently not offering sufficiently precise information and have (not yet) been routinely included in the global NLO fits (see, however, [ 8]). On the other hand, the success of the parton model is based on the universality of parton densities, and one certainly wants to use the information extracted from DIS to make predictions for other process, like polarized $pp$ reactions. For such purposes, a full flavour decomposition is in general required. Therefore, in order to end up with a complete set of parton densities, both [ 3, 4] make further assumptions concerning the polarized quark sea. Even though the two fits differ slightly in some aspects regarding, e.g., the input scale and densities for the evolution, the main conclusions are the same and can be summarized as follows:

- the fits work well, i.e., a very good quantitative description of all data sets is achieved. This is demonstrated in [ 3] Fig. 1;
- the nucleon's singlet axial charge $a_0$ (directly related to the first moment of the flavour-singlet component of $g_1$) comes out to be only about 0.2, implying (to LO) that quarks and antiquarks contribute only little to the nucleon spin. Thus, this finding in the EMC experiment [ 1], which triggered so much theoretical and experimental activity over the last decade, has been confirmed over the years by all successive experiments (see also [ 5]);
- the spin-dependent gluon density $\Delta g$ turns out to be only rather weakly constrained by the data. This is not a very surprising finding since, according to Eq. (2), $\Delta g$ enters $g_1$ only as a NLO correction, and of course indirectly via the $Q^2$-evolution of the parton densities.

Note that on the last point the two fits [ 3, 4] agree to a lesser extent; the error assigned to $\Delta g$ in [ 4] is considerably smaller than in [ 3] and probably does not fully reflect all existing uncertainties. The spread of allowed $\Delta g$ reported in [ 3] is in line with that found in [ 9], where a very careful analysis of all uncertainties, experimental *and* theoretical, was performed.

An interesting possible explanation for the experimental smallness (with respect to constituent quark expectations) of $a_0$ was proposed in [ 10] in terms of a non-perturbative gluonic 'topology' term arising from the non-invariance of the forward matrix elements of the Chern-Simons current $K^\mu$ under 'large' gauge transformations which change the topological winding number. Recall that $a_0$ is given by the forward matrix element of the quark singlet axial vector current $j_5^\mu$, and that $\partial_\mu j_5^\mu = 2f\partial_\mu K^\mu$ is non-zero due to the axial anomaly. This led [ 11] to the interpretation of $a_0$ in terms of the (conserved) quark spin and a gluonic contribution. The topology term proposed in [ 10] goes beyond this picture in the sense that it induces an extra contribution to $a_0$ that has support only at $x = 0$. Consequently, it would have been missed in experimental determinations of the first moment of $g_1$, which might explain the finding of a small $a_0$. However, the topology term would contribute in determinations of $a_0$ in

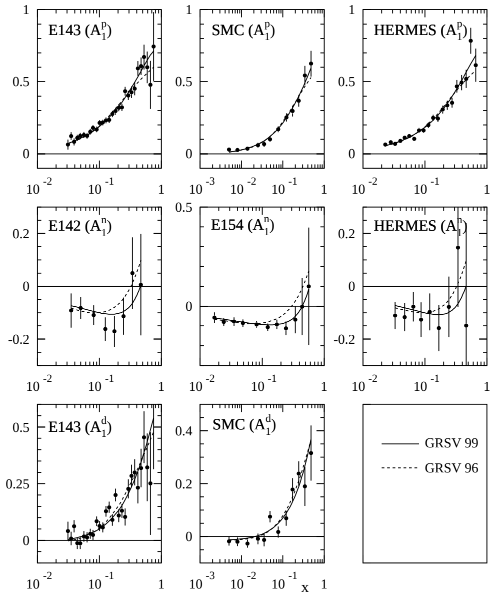


Figure 1. Comparison of data on $A_1(x, Q^2)$ with a NLO QCD fit [3].

$\nu p$ elastic scattering, which implies that it can in principle be measured by comparing with the value for $a_0$ found in polarized DIS.

Two presentations at this workshop dealt with higher-twist contributions to polarized structure functions. This is a very relevant issue since so far all experiments in polarized DIS have been fixed-target experiments, with $Q^2$ values often not significantly higher than a few GeV$^2$. In [ 12], target-mass corrections were calculated for all polarized structure functions of neutral or charged current DIS. In particular, the effects of such corrections on integral relations between polarized structure functions was systematically investigated, and new relations between the twist-3 parts of the spin-dependent structure functions were derived. First numerical results indicate that the target-mass corrections to $g_1$ are clearly non-negligible for $Q^2 \approx 1$ GeV$^2$ and moderate $x$. The knowledge of such kinematical higher-twist terms is also crucial if one wants to experimentally extract *dynamical* higher twists. Dynamical twist-4 contributions to the singlet part of $g_1(x, Q^2)$ were estimated in [ 13] in the context of the infrared renormalon model. Also from this model, non-negligible effects at experimentally relevant $x$ and $Q^2$ are expected.

## 3. OPEN QUESTIONS

### 3.1. Chasing $\Delta g$

As explained above, the nucleon's spin-dependent gluon density $\Delta g$ is presently hardly constrained experimentally. Its presumably important rôle [ 11] in understanding the nucleon spin has placed it in the focus of attention of the spin physics community for a long time. Experiments are being planned now (see [ 2]) which are dedicated to a large extent to a measurement of $\Delta g$. On the theory side, a lot has been done, in particular in the past year, to provide the framework for a reliable (perturbative) description of the key processes to be studied in these experiments. The big improvement here has been the calculation of NLO QCD corrections to the various reactions of interest. Clearly, only if the QCD corrections are under control, can a process that shows good sensitivity to $\Delta g$ at the lowest order level, be regarded as a genuine probe of the polarized gluon distribution and be reliably used to extract it from future data. Furthermore, it is well-known that LO calculations of cross sections in $lN$ or $pp$ collisions are at best semi-quantitative. In particular, they are usually plagued by rather large uncertainties related to the dependence of the theory prediction on the unphysical scales to be introduced in the process of renormalization of the strong coupling and of factorization of mass singularities. In many cases this situation is alleviated to a large extent when going to the next order of perturbation theory. An example of this will be shown below.

To measure $\Delta g$ directly, it is crucial to consider processes in which the gluon enters already at the lowest order, unlike in the case of $g_1$. At the same time, one wants to pick processes that have proven successful in the unpolarized case to constrain the nucleon's unpolarized gluon density $g(x, Q^2)$. Candidate processes, which will be studied experimentally in the future, are:

**(a) Heavy-flavour production.**
In leptoproduction, this process is to LO driven

by photon-gluon fusion, $\vec{\gamma}\vec{g} \to h\bar{h}$, where, in practice, $h = c$ (the arrows indicate from now on a polarized particle). It presumably offers the cleanest signature for $\Delta g$ as far as fixed-target leptoproduction experiments are concerned. It has been one of the original motivations for the COMPASS experiment at CERN [ 2], where one will actually look at charm *photo*production, i.e. at the limit in which the exchanged photon is practically on-shell. The calculation of QCD corrections to polarized heavy-flavour photoproduction has been completed recently and was reported at this conference [ 14]. Note that not only the corrections to the Born channel are involved here, but also a new subprocess, $\vec{\gamma}\vec{q} \to qc\bar{c}$, which is not present at LO. It turns out that, as expected, the QCD corrections are in general sizeable, in particular in the threshold and high-energy regions. However, they become reasonably small in the kinematical regime relevant for the COMPASS experiment. Extension to the case of heavy-flavour production by two polarized protons, is nearing completion. Here, the main LO contribution results from the partonic channel $\vec{g}\vec{g} \to c\bar{c}$, which obviously has strong sensitivity to $\Delta g$. The NLO corrections to this process still need to be completed, while those for the other channel, $\vec{q}\vec{\bar{q}} \to c\bar{c}$, as well as the new NLO process $\vec{q}\vec{g} \to c\bar{c}q$, are already known [ 14]. The full QCD corrections to $\vec{p}\vec{p} \to c\bar{c}X$ will be of great relevance for heavy-flavour experiments to be carried out at the polarized RHIC collider at BNL [ 2].

The NLO QCD corrections to $\vec{\gamma}\vec{g} \to c\bar{c}$ with a *virtual* photon, i.e. the corrections to the charm component $g_1^c$ of the structure function $g_1$, are almost complete as well [ 15]. First numerical results indicate that the relative contribution of $g_1^c$ to the total $g_1$ is smaller than that of $F_2^c$ to $F_2$ in the unpolarized case. This is readily understood from the fact that there are oscillations of the relevant coefficient functions due to the sum rule $\int dz H_g^S(z) = 0$ for charm production off an initial polarized gluon [ 15].

**(b) Polarized photoproduction of jets.**
The process $\vec{e}(\vec{\gamma})\vec{p} \to jet(s)X$ would be accessible experimentally [ 16] after an upgrade of the HERA collider to having a polarized proton beam in addition to the already polarized electron beam. Again, it has a LO contribution sensitive to $\Delta g$: $\vec{\gamma}\vec{g} \to q\bar{q}$. Complications arise due to the fact that, as is well-known from the unpolarized case, the photon will not only interact in a 'point-like' (direct) way, but also via its partonic structure ('resolved' component). Nothing is known so far experimentally about the spin-dependent parton densities $\Delta f^\gamma$ of the polarized photon. On the one hand, this limits our predictive power for this process; on the other hand, it makes the process and its experimental study even more fascinating, since a measurement of the $\Delta f^\gamma$ in future photoproduction experiments at polarized HERA appears feasible [ 16].

NLO QCD corrections are expected to be particularly important for the case of jet production, since it is only at NLO that the QCD structure of the jet starts to play a rôle in the theoretical description, providing for the first time the possibility, and necessity, to realistically match the experimental conditions imposed to define a jet. In [ 17] the calculation of the QCD corrections to polarized single-inclusive photoproduction of jets, both for the 'direct' and the 'resolved' components, was reported. The corrections are found to be particularly important in the region of negative rapidities of the jet, where the 'direct' component dominates. Also, the expected strong reduction in scale dependence of the cross section when going from LO to NLO was verified.

**(c) Jet production in polarized *pp* collisions.**
This process presumably offers one of the most promising ways to measure $\Delta g$ at RHIC. It combines a potentially strong sensitivity to $\Delta g$, thanks to the partonic LO channels $\vec{q}\vec{g} \to qg$ and $\vec{g}\vec{g} \to q\bar{q}(gg)$, with a large event rate, which results in rather small expected statistical errors on the corresponding spin asymmetry. Indeed, this is exactly what is found in the theory studies presented [ 17] here. Fig. 2 shows the asymmetry for single-inclusive jet production for various sets of spin-dependent parton densities, which differ mainly in the size of $\Delta g$. In addition, the smallest jet asymmetry that can be measured experimentally at RHIC for $\mathcal{L} = 100$ pb$^{-1}$ is indicated

by the open blocks. It is obvious that jet measurements at RHIC will be in the position to pin down $\Delta g$. Fig. 3 demonstrates the significant reduction in scale dependence at NLO, which makes the theory predictions much more reliable.

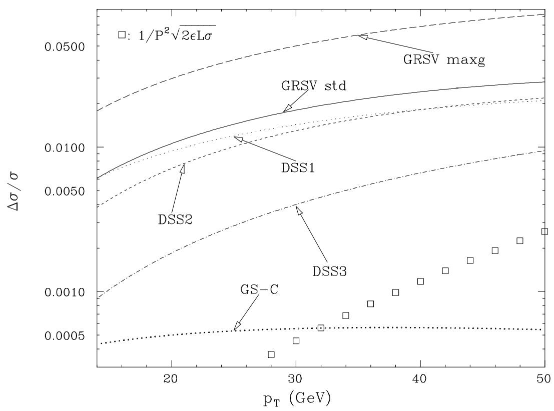


Figure 2. NLO single-inclusive jet asymmetries in $\vec{p}\vec{p}$ collisions at RHIC, for various polarized parton densities [17].

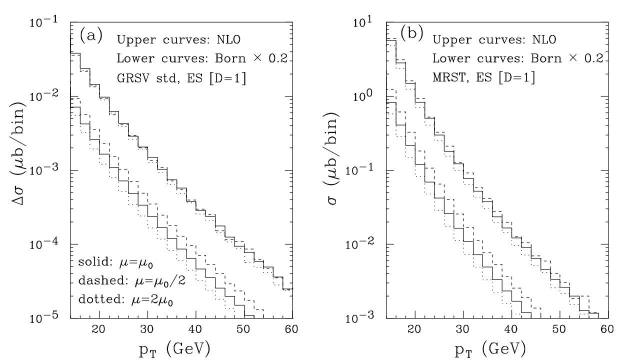


Figure 3. Scale dependence of the NLO and LO jet $p_T$-distributions in $\vec{p}\vec{p}$ collisions [17].

**(d) Prompt photon production.**
The production of high-$p_T$ 'prompt' photons in unpolarized hadron-hadron collisions has historically been considered as *the* probe of the hadrons' gluon density. Data have been the backbone of the gluon determination in many analyses of parton densities. This is thanks to the presence and dominance of the LO 'Compton' process $qg \to \gamma q$ and the alleged 'cleanliness' of the photon final state. These features make prompt photon production in $\vec{p}\vec{p}$ collisions at RHIC the most promising candidate for a measurement of $\Delta g$. However, there are caveats: firstly, the process is not as clean as it might look superficially: there is also a contribution for which a final-state quark or gluon, produced in a hard pure-QCD subprocess, *fragments* into a photon. The photon fragmentation functions are only insufficiently known at present, which sets a limitation to our predictive power for the prompt photon process. The situation is alleviated somewhat by the fact that in prompt photon experiments at colliders, an 'isolation cut' is imposed on the photon in order to reduce the huge background from the copiously produced $\pi^0$. Traditionally, this is defined by drawing a cone of fixed aperture around the photon, and by restricting the hadronic energy allowed in this cone. In this way the fragmentation component, which results from an essentially collinear process, is diminished; however it still remains non-negligible. A way out of this dilemma was proposed at this conference [ 18]: by refining the isolation cut to the extent that one allows *less and less* hadronic energy the closer to the photon it is deposited, until eventually *no* energy at all is allowed exactly collinear to the photon, it is possible to define an isolated prompt photon cross section that is entirely independent of any fragmentation component. This definition of isolation has therefore a clear advantage over the traditional one. It should be possible to implement it in experiment without too much effort. Phenomenological applications at RHIC energies look very promising [ 18] as far as the possibilities of measuring $\Delta g$ are concerned.

A potentially more hazardous problem concerning the prompt photon process at RHIC is that in the unpolarized case the agreement between theory and some of the most precise data sets [ 19] is rather poor and sometimes even appallingly bad. Clearly, if this situation persists, one will have to worry whether in the polarized case one can really interpret future data straightforwardly in terms of $\Delta g$. Without going any further into the discussion on the situation in the unpolarized case, it should be emphasized that in view of the present experimental and, in particular, theoretical efforts [ 20] in this field, it seems likely that the theoretical description of

prompt-photon production will be in much better shape by the time RHIC will deliver first data on $\vec{p}\vec{p} \to \gamma X$.

### 3.2. Transversity and Drell-Yan dimuon production

Apart from the unpolarized and longitudinally polarized parton densities, a third type of twist-2 parton distribution of the nucleon can be defined, the 'transversity' density [ 21, 22] $\Delta_T q(x, Q^2)$. In a transversely polarized nucleon it counts the number of quarks with spin aligned parallel to the nucleon spin minus the number of quarks with opposite polarization. Unfortunately, nothing is known as yet experimentally about the transversity distributions. Technically speaking, they are 'chiral-odd', that is, a helicity-flip of the quark-line is required in the hard process [ 22] that probes the $\Delta_T q$. This property makes the transversity densities inaccessible in fully inclusive DIS. Drell-Yan lepton pair production in collisions of transversely polarized protons offers a possibility to get access to the $\Delta_T q$ [ 21, 22], and the RHIC spin physics program comprises experiments of this kind.

A 'positivity' inequality for the $\Delta_T q(x, Q^2)$ has been derived in [ 23] in terms of the unpolarized and longitudinally polarized quark densities: $|\Delta_T q(x, Q^2)| \leq (q(x, Q^2) + \Delta q(x, Q^2))/2$, which may be used for modeling the $\Delta_T q$ when making predictions for future experiments. This inequality is preserved by NLO DGLAP evolution in the $\overline{\mathrm{MS}}$ scheme, as discussed in [ 24] in terms of a 'gain-loss' equation.

Interesting information on the tensor charge of the nucleon, which is related to the first moment combination $\delta q \equiv \int_0^1 dx(\Delta_T q - \Delta_T \bar{q})(x, Q^2)$, was recently obtained in lattice calculations [ 25]. It turns out that the quantity $\delta u - \delta d$, after conversion to a renormalization-group invariant, is rather similar to the corresponding non-singlet contribution of $u$ and $d$ flavours to the proton's *axial* charge on the lattice; see Fig. 4. Note though that the latter should come out as $g_A \approx 1.26$, which does not happen satisfactorily, presumably as a result of the quenched approximation used in the calculation [ 25].

Phenomenological NLO predictions for the

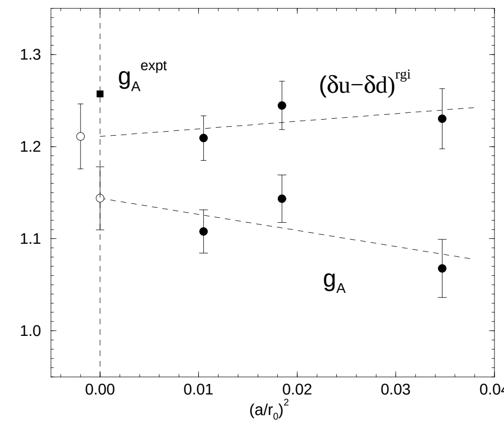


Figure 4. The continuum limit for $g_A$ and $(\delta u - \delta d)^{rgi}$ [25].

Drell-Yan process with transversely polarized protons were presented at this workshop in [ 26, 27]. In [ 26], *saturation* of Soffer's inequality at a low input scale for the evolution was assumed in order to model the transversity densities. With some justification, this approach can be expected to predict the maximally possible spin asymmetries for the Drell-Yan process. These asymmetries turn out to be of the order of a few per cent. The expected statistical errors for such measurements at RHIC or HERA-$\vec{\mathrm{N}}$ turn out to be smaller than the asymmetry by a factor of $2-3$ in the optimal case; see Fig. 5. A possible flavour ($\Delta_T \bar{u}$, $\Delta_T \bar{d}$) separation of the transversity sea in dimuon production was discussed in [ 27], the proposed tool for this being the ratio $\Delta_T \sigma^{pd}/2\Delta_T \sigma^{pp}$ of Drell-Yan cross sections; however, the experimental feasibility appears unlikely, also in view of the findings of [ 26].

The Drell-Yan process also was the main topic in [ 28, 29]. In [ 28], the production of dimuon pairs was studied for the case of 'LT'-collisions of transversely polarized protons with longitudinally polarized ones. The description involves interesting twist-3 structure functions. Employing bag model predictions and large-$N_C$ evolution for the latter, estimates for the corresponding spin-asymmetry $A_{LT}$ are obtained which are much smaller than those for $A_{TT}$ found in [ 26]. Many new, yet unexplored, structure functions appear if the Drell-Yan process is studied in polarized

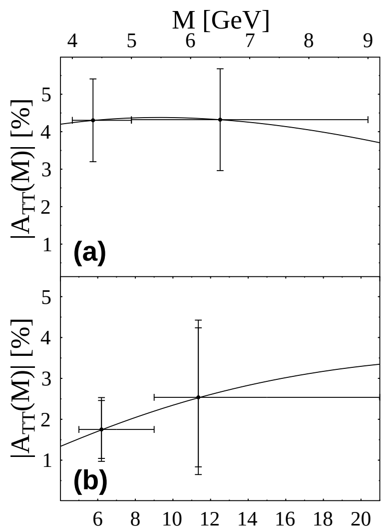


Figure 5. The 'maximal' double-spin asymmetry for the Drell-Yan process in collisions of transversely polarized protons at (a) HERA-$\vec{\mathrm{N}}$ and (b) RHIC, as a function of the dimuon mass $M$ [26].

proton-deuteron scattering, thanks to the spin-1 nature of the deuteron [ 29].

### 3.3. Orbital angular momentum, DVCS, and off-forward parton distributions

It will only really be justified to refer to the spin structure of the nucleon as 'understood' if also the contributions resulting from the orbital angular momenta $L_{q,g}$ of quarks and gluons will have been determined. As was discovered in [ 30], the *total* angular momenta (i.e., integrated over all Bjørken-$x$) carried by quarks and gluons, $\Delta\Sigma/2 + L_q$ and $\Delta G + L_g$, respectively, can in principle be determined in 'deeply-virtual Compton scattering' (DVCS) $\gamma^* P \to \gamma P'$: the explicit presence of $x^\mu$ in the corresponding terms of the QCD angular momentum tensor forces one to go to the off-forward region [ 31]. Things become more complicated if one considers 'parton distributions' of orbital angular momentum, i.e. $L_{q,g}$ as functions of Bjørken-$x$. As pointed out in [ 31], one encounters the dilemma here that such quantities can indeed be consistently defined [ 32], but that presently no way of observing them in experiment has been discovered. Vice versa, quantities that *can* in principle be measured in DVCS, do not directly find their interpretation in terms of $L_{q,g}(x)$ [ 31].

The DVCS amplitude itself was discussed in several talks at this workshop. In [ 33], its asymptotic properties in the very forward and backward regions were studied, resumming the large logarithms arising. The most general DVCS process, $\gamma^* P \to \gamma^{*'} P'$ was examined in [ 34] in a 'generalized' Bjørken region with $-(q_1+q_2)^2/4\nu$ and $(q_1^2 - q_2^2)/2\nu$ as scaling variables, $q_1$, $q_2$ being the photon momenta. The technical tool employed here is the 'nonlocal light-cone expansion', which was also the motivation for [ 35], where a way of systematically decomposing nonlocal light-cone operators into contributions of definite twist was presented. In the forward case the analysis of [ 34] recovers the known integral relations between polarized DIS structure functions.

Being generalizations of the usual parton densities, off-forward parton distributions break Bjørken scaling as soon as QCD radiative corrections are taken into account. The resulting evolution equations were studied in [ 36], where even the *next-to-leading* order anomalous dimensions were included. Remarkably, a way of deriving these was found that avoids the involved calculation of explicit two-loop diagrams, but makes clever use of conformal covariance, the known two-loop anomalous dimensions for the forward case, and the recognition that the breaking of conformal invariance (which takes place at the NLO level) can be accounted for by calculating *one-loop* conformally anomalous terms. First numerical results in the non-singlet sector indicate that the NLO terms induce only very mild corrections to LO evolution; however, as with many things, the calculation has to be done before one can tell! In [ 37], a complete set of $\mathcal{N}=1$ supersymmetric constraints for the anomalous dimensions of conformal twist-2 operators was presented. As an application, the ER-BL evolution [ 38] kernel at NLO in the parity-odd sector, which governs both the evolution of the corresponding singlet meson distribution amplitude and of the off-forward distribution, was derived without any evaluation of a two-loop diagram.

### 3.4. Spin-dependent fragmentation functions

Studies of spin-transfer reactions provide insight into the field of 'spin physics' from a different angle. Rather than asking for the 'spin-up minus spin-down' distribution of, say, a quark in a polarized proton, one is primarily interested here in the fragmentation counterpart, i.e. the distribution of a polarized (spin-$\frac{1}{2}$) hadron $h$ in a polarized parton $f$,

$$\Delta D_f^h(z,Q^2) \equiv D_{f(+)}^{h(+)}(z,Q^2) - D_{f(+)}^{h(-)}(z,Q^2) \ . \quad (3)$$

Obviously, access to such quantities is only possible if one is able to measure the polarization of $h$. $\Lambda$-baryons are particularly suited for such studies due to the self-analyzing properties of their dominant weak decay $\Lambda \to p\pi^-$. Recent LEP measurements [ 39] of the polarization of $\Lambda$'s produced in $e^+e^-$ annihilation, have demonstrated the experimental feasibility of reconstructing the $\Lambda$ spin. Here, *no* polarization of the initial beams is required since the parity-violating $q\bar{q}Z$ coupling automatically generates a net polarization of the quarks that fragment into the $\Lambda' s$.

At the moment, the sparse data available from LEP are by far not sufficient to constrain the $\Delta D_f^\Lambda$ significantly. Various reactions that might be employed for obtaining independent information have been discussed in [ 40] at this workshop, and phenomenological predictions for them were presented, based on conceivable sets of $\Delta D_f^\Lambda$ proposed in [ 41]. These include semi-inclusive DIS, $\vec{e}p \to \vec{\Lambda}X$, and in particular $\vec{p}p \to \vec{\Lambda}X$. The latter reaction could be studied at RHIC, and the prospects are very promising as far as the expected statistical errors are concerned in comparison to the actual possible size of the spin-transfer asymmetry. This holds true for longitudinal as well as for transverse polarization of the proton beam and the $\Lambda$. Finally, interesting information on the flavour decomposition of the $\Delta D_f^\Lambda$ could also be obtained in $\nu$, $\bar{\nu}$ semi-inclusive DIS [ 40].

### 3.5. Transverse single-spin asymmetries

The understanding of single-spin asymmetries for processes like $p^\uparrow p \to \pi X$, $lp^\uparrow \to \pi X$, etc. ($\uparrow$,$\downarrow$ denoting transverse polaj9iysrization) is another interesting challenge. Experimentally, the study of such asymmetries is simpler than that of double-spin asymmetries, for obvious reasons. On the theoretical side, within the 'normal' framework of perturbative QCD and the factorization theorem at leading twist for collinear parton configurations, no non-zero single-spin asymmetry can be constructed for parity-conserving processes. However, it has been recognized for a while now [ 42, 43, 44] that possible origins of single-spin asymmetries may be found in the dependences of parton distribution and fragmentation functions on intrinsic parton transverse momentum $k_T$. Under the crucial assumption that a factorization theorem can be invoked even when not integrating out $k_T$, one can rather successfully set up a hard-scattering model to describe the single-spin asymmetries in terms of the usual convolutions of perturbatively calculable partonic hard-scattering cross sections with various, now $k_T$-dependent, parton densities and fragmentation functions [ 45, 44]. The set of the latter is bigger than the one of the usual ($k_T$ integrated) distributions considered in the previous sections. For instance, one may have [ 45, 44], in fairly obvious notation,

$$\begin{aligned}\Delta^N D_{h/q} &= D_{h/q^\uparrow}(z,\boldsymbol{k}_\perp) - D_{h/q^\downarrow}(z,\boldsymbol{k}_\perp) \ , \\ \Delta^N f_{q/p^\uparrow} &= f_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) - f_{q/p^\downarrow}(x,\boldsymbol{k}_\perp) \ , \\ \Delta^N f_{q^\uparrow/p} &= f_{q^\uparrow/p}(x,\boldsymbol{k}_\perp) - f_{q^\downarrow/p}(x,\boldsymbol{k}_\perp) \ , \end{aligned} \quad (4)$$

all of which integrate to zero over $k_T$ and are $T$-odd. For the single-spin asymmetry in $p^\uparrow p \to \pi X$, all of the three functions in (4) might be at work and correspond to the Collins effect [ 43], Sivers effect [ 42], and the effect proposed in [ 44], respectively. There is a qualitative difference between the first mechanism and the other two in that, in order to be able to produce an effect, the latter rely on the presence of some kind of initial-state interactions between the incoming particles, whereas the Collins effect just requires *final*-state interactions (which are certainly present), to make the overall process time-reversal symmetry conserving. This makes the Collins effect perhaps a more likely source for single-spin asymmetries in general, and definitely for reactions with a lepton-nucleon initial state. In consequence, in [ 45] the present data for the single-spin asymmetry in

$p^{\uparrow}p \to \pi X$ were fitted just in terms of the Collins effect, and the resulting $D_{h/q^{\uparrow}}(z, \boldsymbol{k}_{\perp})$ was then used to predict the asymmetry in semi-inclusive single-spin DIS, $lp^{\uparrow} \to \pi X$. Large asymmetries are found for HERMES kinematics; see Fig.6. Note though that the $p_T$ of the pion considered here is only just larger than 1 GeV, which raises some concern as to whether the hard-scattering mechanism employed is fully appropriate.

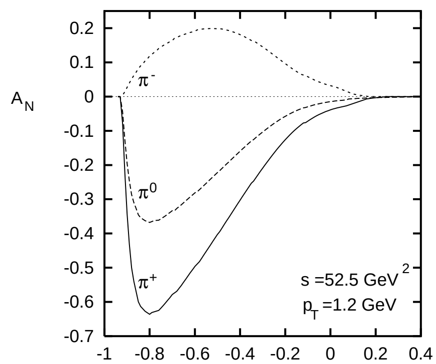


Figure 6. Predictions for the transverse single-spin asymmetry $A_N(lp^{\uparrow} \to \pi X)$ as a function of Feynman-$x_F$ for typical HERMES kinematics [45].

Distributions similar to the first two in (4) were considered in [ 46], where $k_T^2$-weighted integrals of the functions were used to study azimuthal asymmetries in DIS, like the one presented by the HERMES collaboration at this workshop (see [ 2]).

The Collins effect has been studied using LEP data on $Z^0 \to$ 2jet decay [ 47]. Here one exploits that the transverse polarizations of the produced quark and antiquark are correlated as $(v_q^2 - a_q^2)/(v_q^2 + a_q^2)$. The magnitude of the Collins effect is represented by the analyzing power [ 47, 48] $A \equiv |\Delta^N D_{\pi/q}|/D_{\pi/q}$, i.e. the ratio of the fragmentation function introduced in Eq.(4) over the unpolarized one. Preliminary results suggest $A$ to be clearly non-zero.

As was shown in [ 44], the function $\Delta^N f_{q^{\uparrow}/p}$ in (4) (named $h_1^{\perp}$ there) also offers a possible explanation for an anomalously large $\cos(2\phi)$ dependence of the unpolarized Drell-Yan cross section found by the NA10 collaboration [ 49]. Note that for the Drell-Yan process the Collins effect is clearly not involved. Furthermore, *single-spin* Drell-Yan measurements at RHIC are sensitive to the convolution $\Delta^N f_{q^{\uparrow}/p} \otimes \Delta_T q$ and might therefore be useful to constrain the transversity densities [ 44].

### 3.6. Two further topics in spin physics

The spin structure of the *photon* is another interesting topic in spin physics, about which no experimental information is available yet. The case of polarized (quasi)real photons was studied a few years ago [ 50], and it was shown that the corresponding polarized parton densities would be accessible in jet-photoproduction experiments at a polarized HERA collider [ 16]. At this conference, predictions for the structure function $g_1^{\gamma}(x, Q^2, P^2)$ of a photon that is off-shell by $-P^2$, were presented [ 51]. Only the perturbative ('point-like') part was considered. The first moment, $\int_0^1 dx g_1^{\gamma}(x, Q^2, P^2)$, comes out non-vanishing, unlike in the case of real photons.

The possibilities of analyzing the chiral structure of various conceivable leptoquark models using a polarized HERA collider or even a polarized TESLA$\otimes$HERA machine were examined in [ 52]. The tool to do this would be the parity-violating DIS asymmetry $A^{PV} = (\sigma_{NC}^{--} - \sigma_{NC}^{++})/(\sigma_{NC}^{--} + \sigma_{NC}^{++})$, where superscripts denote electron and proton helicities. For an unambiguous separation of the various models, polarized *en* collisions would be required in addition to *ep* ones.

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Note concerning the references: For most talks we just refer to the contribution to the proceedings, and mention only the author who actually presented the talk. For the other authors and/or for previously published papers on the same topic by the author(s), please consult their actual contribution.

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